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Arun K. Somani
*Iowa State University*, arun@iastate.edu

David Lastine
*Iowa State University*

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## Abstract

Light-trails based solutions have been proposed and demonstrated as a means of traffic grooming and optical multicasting in a LAN/MAN, where multiple nodes use time division multiple access on a unidirectional optical bus. When compared to light paths or having nodes relaying traffic using optical-electronic-optical conversion there are advantages and disadvantages to light-trails in terms of bandwidth, hardware requirements and latency. Given that a light-trail of a specific length has been identified, we develop an approach to increase its capacity utilization. In particular, we show that splitting a longer light-trail in shorter segments results into more effective and efficient utilization of bandwidth. However, we do not believe that splitting a light-trail into segments of lengths one is preferable as it will increase the overall delay.



## Keywords

local area networks, metropolitan area networks, multicast communication, optical communication, system buses, telecommunication traffic

## Disciplines

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## Comments

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# Determining Optimal Light-Trail Length

Arun K. Somani and David Lastine
Department of Electrical and Computer Engineering
Iowa State University, Ames, Iowa 50011
Email: {arun, dlastine}@iastate.edu

***Abstract*— Light-trails based solutions have been proposed and demonstrated as a means of traffic grooming and optical multicasting in a LAN/MAN, where multiple nodes use time division multiple access on a unidirectional optical bus. When compared to light paths or having nodes relaying traffic using optical-electronic-optical conversion there are advantages and disadvantages to light-trails in terms of bandwidth, hardware requirements and latency. Given that a light-trail of a specific length has been identified, we develop an approach to increase its capacity utilization. In particular, we show that splitting a longer light-trail in shorter segments results into more effective and efficient utilization of bandwidth. However, we do not believe that splitting a light-trail into segments of lengths one is preferable as it will increase the overall delay.**

## I. Introduction

Wavelength Division Multiplexing (WDM) has emerged as the dominant technology in backbone networks. Current WDM networks are ring or mesh networks that are interconnected by optical crossconnects. The network principle is based on lightpaths, i.e. a single path interconnecting the source and destination node using the same wavelength on each link without wavelength conversion at the intermediate nodes or possible different wavelength on links if wavelength conversions are used. No traffic is added or dropped or tapped at the intermediate nodes. The lightpath principle leads to a low carried load on each wavelength since a single connection can rarely utilize the full available capacity.

Light-trails [1], [2] have been proposed to enable all intermediate nodes to use the available capacity while serving IP-centric [3], [4] and multicast communications [5] at the optical layer. A light-trail is a unidirectional optical bus setup between the convener (start) node the terminator (end) node as shown in Figure 1 from node 0 to node $n-1$. A reverse light-trail can be set in the opposite direction.

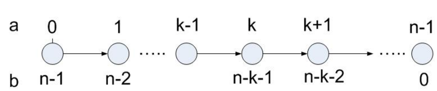


Fig. 1. A light-trail from node $n-1$ to node 0

A light-trail is similar to a lightpath with one important difference that the intermediate nodes can also access(add or tap the traffic) the unidirectional bus. The upstream node can send data to any of its downstream nodes without the need for optical switch reconfiguration. Every node receives the data from the upstream nodes, but only the corresponding destination node(s) will accept the data packets while other nodes ignore them. More detailed information is provided in the paper [1], which has defined the light-trail architecture. In [2] Multiprotocol Label Switching (MPLS), Optical Burst Switching (OBS), and Optical Packet Switching (OPS) are discussed in detail along with the advantages of light-trails over these methods and average light-trail length vs link load along with number of connections are examined. The use of light-trails to support a multicast session is discussed in [5]. Authors in [6] discussed the optimized usage of optical transceivers and traffic grooming in light-trails to reduce network cost. Several results have been reported in designing and/or embedding optimal light-trail to manage a given traffic in networks [7], [8], [9], [10], [11]. Experimental systems demonstrating light-trails have been reported in [12], [13].

Given that a light-trail has been designed to be of certain length, we in this paper discuss methods to manage traffic more efficiently. The approach we take is to show that splitting an established light-trail into two or three segments allow space multiplexing and yield higher capacity utilization. This implies store and forward or relaying of traffic at the intermediate nodes on the identified light-trail. However, we do not believe that splitting a light-trail into segments of lengths one is preferable as it will increase the overall delay. Our solution provides an approach to enhance the capacity of the system if needed on a light-trail.

The rest of the paper is organized as follows. Section II describes the problems of Light-trail bandwidth utilization. Section III of the paper examines how shorter light-trails segments with relay nodes connecting them keep the benefits of space division multiple access (SDMA) high when all possible connections have a fixed bandwidth. The paper is concluded in Section IV.

## II. Light-Trail Bandwidth Problem

It is a desirable goal to use network resources as efficiently as possible to minimize the total amount of resources used to carry a specified amount of traffic. This reduced the overall construction, operation and maintenance costs of a network. The efficient use of bandwidth on a wavelength presents a challenge in that individual users need bandwidth in the mega-bit range where data rates on a single wavelength can be up to 40 giga-bit per second. Users typically only wish to communicate to one or possible a few nodes. Both space and time division multiplexing are employed to utilize a wavelength efficiently. Traffic distributions can cause techniques that utilize one type of multiplexing well to ignore or harm the benefits of using the other.

One way that bandwidth is divided is by having node pairs establish light paths between them and aggregate traffic from multiple users onto these high speed paths. This minimizes space use of a wavelength. However, there is no reason in general to assume that the demand between two nodes will be the same as the data rate supported on a light path. Thus some of the bandwidth on a wavelength may be wasted.

If a light path only uses a fraction of a wavelength bandwidth, the intermediate nodes on that path are not able to use the unused fraction of the bandwidth. This motivates the idea of light-trails where time division multiplexing is deployed to allow intermediate nodes to transmit traffic. Depending on traffic in the network a light-trail may use a wavelength more efficiently than a light path. A light-trail is less efficient at using space division multiplexing (SDMA) since it prevents node pairs on physically disjoint segments of the light-trail from using the wavelength simultaneously. For example, consider a light-trail $s\ ,\cdots,\ s_1,\cdots,d_1,\cdots,s_2,\cdots,d_2,\cdots,d$. If source node $s_1$ wants to transmit data to destination node $d_1$ and source node $s_2$ wants to transmit data to destination node $d_2$, they cannot transmit data simultaneously.

To keep the advantages provided by light-trails in terms of time division multiple access (TDMA), without suffering much loss in terms of space division multiple access (SDMA), light-trails can be split into multiple short segments where traffic is relayed electronically instead of continuing on optically as discussed in the next section.

## III. Capacity Benefits of Light-Trail Splitting

This section examines the relationship between light-trail length (total number of links on a light-trail) and capacity available per node when every node has a constant bandwidth connection to every other node.

### A. Motivational Examples

To illustrate the gains in bandwidth provided by splitting a light-trail, consider a seven node light-trail with nodes numbered from node 0 to node 6. We refer to attributes of this seven node light-trail with the subscript unsplit. If this seven node system is modified to consist of two light-trails where traffic can be relayed from one to the other, its attributes are referenced as split.

There are $n(n-1)/2$ connection pairs that can be satisfied by a unidirectional light-trail of $n$ nodes. Thus there are 21 connection pairs possible so a light-trail supporting all seven nodes can carry $21c_{unsplit}$ units of bandwidth, where $c_{unsplit}$ is the bandwidth allocated to each connection. In the case of a relay node, which splits the seven node light-trail into two light-trails with a relay at node node 3, the managed traffics reduces. This is because all traffic that originates and is consumed in segment from node 0 to node 3 does not use any optical bandwidth in segment from node 3 to node 6. In the same way all traffic generated at or after node node 3 does not use optical bandwidth in segment node 0 to node 3. The first light-trail only need to serve $15c_{unsplit}$ units of traffic, $6c_{unsplit}$ on them is used internally and $9c_{unsplit}$ is relayed by node 3 to the other light-trail. The second light-trail also carries $15c_{unsplit}$ units, $9c_{unsplit}$ from the first light-trail and $6c_{unsplit}$ generated at nodes 3, 4, and 5. Using only $15c_{unsplit}$ traffic on each segment is a waste of available optical bandwidth. This waste is avoided by giving each connection a allocation of $c_{split}$ bandwidth where $c_{split}=\frac{21}{15}c_{unsplit}$ units of bandwidth. This shows that shorter light-trails and relaying can provide higher bandwidth per connection.

By extending the above argument to an eight node light-trail, there are 28 connection pairs possible, so a light-trail will require $28C_{unsplit}$ units of bandwidth. Table I illustrate the actual bandwidth needs on a wavelength if optical-electronic-optical (OEO) conversion is used instead of a light-trail. Note that node seven is the last node and as such sends no traffic. Each column is headed by a reference to which node is source of a connection, and each row shows how many of those connections need to be relayed using OEO to emulate a light-trail. An eight node light-trail would save the cost of OEO relaying at all of its node at the cost of only being able to utilize between $\frac{16}{28}$ to $\frac{7}{28}$ fraction of available bandwidth on its various links.

| Nodes | $S_0$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | Total |
|---|---|---|---|---|---|---|---|---|
| $T_0$ | 7 | | | | | | | 7 |
| $T_1$ | 6 | 6 | | | | | | 12 |
| $T_2$ | 5 | 5 | 5 | | | | | 15 |
| $T_3$ | 4 | 4 | 4 | 4 | | | | 16 |
| $T_4$ | 3 | 3 | 3 | 3 | 3 | | | 15 |
| $T_5$ | 2 | 2 | 2 | 2 | 2 | 2 | | 12 |
| $T_6$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 |
| $T_7$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

TABLE I
Bandwidth requirement between nodes in a light-trail

### B. Effect of Splitting a light-trail once

Consider an $n$ node light-trail, with nodes numbered 0 to $n-1$ as shown in Figure 1. Let there be a node $k$ at which the light-trail will be split into two segments, where traffic between the two post split light-trails must undergo optical-electronic-optical conversion at node $k$ to travel between the two segments. All node pairs have a connection between them, each connection requires the same amount of bandwidth which we shall denote as $c$ units of bandwidth.

Traffic supported by the light-trail is

$$\frac{cn(n-1)}{2} \tag{1}$$

Figure 1 shows nodes indexed by both variables $a$ and $b$. Equation 2 gives the traffic which is generated and consumed internally by nodes 0 to $k$ by summing the amount of traffic each node is consuming, where nodes are numbered using index $a$.

$$\sum_{a=1}^{k} ca = \frac{ck(k+1)}{2} \quad (2)$$

There are two kinds of traffic for the first segment of light-trail. Internal traffic is the one which is generated by the nodes in the segment and destined for the nodes in the same segment. The traffic generated by the nodes in the segment of light-trail and consumed by nodes not in the segment is called external.

Traffic which is generated and consumed internally by nodes $k$ to $n-1$ is given by Equation 3. The left hand side of this equation comes from totaling traffic generated at nodes for downstream nodes, where nodes are indexed using $b$ shown in Figure 1.

$$\sum_{b=1}^{n-k-1} cb = \frac{c(n-k)(n-k-1)}{2} \quad (3)$$

The correctness of equations 2 and 3 can be seen from Figure 1 where each index numbers nodes differently as shown. *Lemma 1.* For uniform traffic, a light-trail must be split in the middle to maximize the capacity gain.

*Proof.* For the two segments to carry equal traffic, we set the traffic of the left and right segment equal and solve for $k$. The solution turns out to be $k = \frac{n-1}{2}$. The case of $k = \frac{n}{2}$ produces the more even traffic split. If $n$ is odd, then the two light-trails will support equal traffic if node $k$ is selected to be the exact middle node. If $n$ is even, then $k = \frac{n-1}{2}$ is not an integer and the two possible solutions are $k = \frac{n-2}{2}$ or $k = \frac{n}{2}$. The larger segment will handle traffic = $\frac{n}{8}(3n-2)$ and the smaller segment will handle traffic = $\frac{n}{8}(3n-6)$. The difference in the traffic on the two sides is $\frac{n}{2}$.

### C. Cost of Splitting

Traffic which is generated by nodes with number lower than $k$ and is received at nodes higher than $k$ is $ck(n-k-1)$. Therefore if node $k$ is equipped with enough electronic buffering to store and forward $ck(n-k-1)$ units of traffic, a light-trail split at node $k$ will consist of two light-trails, one on the left (nodes 0 to $k$) handles traffic $c\frac{k}{2}(2n-k-1)$ and the one on the right (nodes $k$ to $n-1$) handles traffic $c(n-k-1)(\frac{n+k}{2})$.

The buffering requirements given here hold even if the two light-trails where to be further split as is considered in other sections of this paper.

### D. Effect of Splitting a light-trail Several Times

A light-trail may be split multiple times. Let $K$ be a set of splitting nodes with members $k_i$ where $k_i$ is present if and only if the $kth$ node of a trail is to be used for splitting. In this section we will drop the references to connection capacity $c$ and assume it to be one.

Figure 2 shows a light-trail that can be split into multiple segments, with one sub light-trail being defined by splitting nodes $k_i$ and $k_j$. There is no node in $K$ such that $k_i < k_y < k_j$. Traffic on the trail [$k_i$ , $k_j$] falls into four categories: traffic that is produced and consumed internally, traffic that is produced internally and sent downstream, traffic that came from upstream and consumed internally, and traffic that came from upstream that is headed downstream. The

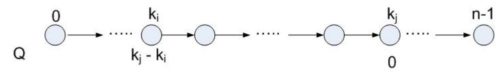


Fig. 2. A light-trail split into several light-trails

traffic generated and consumed internally is:

$$\sum_{Q=0}^{k_j-k_i} Q = \frac{(k_j-k_i)(k_j-k_i+1)}{2} \quad (4)$$

All nodes in the new light-trail produce traffic for every node on the unsplit light-trail after $k_j$. The contribution from $k_j$ is zero since it can transmit directly onto the next light-trail. So the internally generated traffic for the later nodes is given by:

$$(k_j-k_i)(n-k_j-1) \quad (5)$$

Since every node before $k_i$ transmits to every node after $k_j$, the light-trail [$k_i$ , $k_j$] must handle traffic proportional to the produce of the number of preceding and successor nodes.

$$k_i(n-k_j-1) \quad (6)$$

A light-trail segment also receives traffic for its nodes that came from previous light-trail. This traffic amounts to $(k_i)(k_j-k_i)$. In total the traffic a segment of the split light-trail must carry:

$$(\frac{(k_j-k_i)(k_j-k_i+1)}{2} + k_j(n-k_j-1) + (k_i)(k_j-k_i)) \quad (7)$$

This can be rewritten as:

$$\frac{-k_i^2}{2} - \frac{k_i}{2} - \frac{k_j^2}{2} + k_j n - \frac{k_j}{2} \quad (8)$$

Examining the derivative of Equation 8 with respect to $k_i$ shows that moving the end point of a segment results in uneven jumps in the amount of traffic a segment must carry so it is not realistic to expect to be able to be able to divide a light-trail into segments that carry equal amount of traffic. Selecting which segments should carry more traffic and which should carry less should be done based on how splitting will effect delay seen by traffic.

### E. Limiting Case

Splitting reaches its limit when each link is a light-trail. To support the traffic each node $i$ must transmit its own traffic as well as traffic from nodes 0 to $i-1$ to nodes $i+1$ to $n-1$. This gives a total of $(i+1)((n-1)-i)$. Finding the node with most traffic by setting the derivative to zero.

$$\frac{d}{di}(i+1)(n-1-i) = -2i+n-2 = 0 \quad (9)$$

Solving for $i$ tells us the node $\frac{n-2}{2}$ will have the largest load. The ratio between this amount of traffic and the total traffic is:

$$\frac{\frac{n^2}{4}}{\frac{n(n-1)}{2}} = \frac{n}{2(n-1)} \tag{10}$$

Let us consider how traffic is managed on a split light-trail. It is preferred that a node transmit traffic for connection in the next segment first so that the relay node can start transmitting that traffic to the respective destination. After that nodes transmit traffic for destinations within the same segments. Consider a node $i$ that needs to send traffic to two arbitrary nodes $j,\ k$ such that $j < k$ on the original light-trail. If nodes $j$ and $k$ are in two different segments, then node $k$ will transmit its traffic for node $k$ first and then for node $j$ to minimize store-and-forward delay.

### F. The Need For Approximations

The case of splitting a light-trail in half with uniform traffic is a special case in that it can be done such that each side has almost exactly the same amount of traffic. Consider the problem from the perspective of the length of the segments the light-trail is broken into. Let us call the segments $\alpha$ and $\beta$ where the last node in one segment is the first in the other as shown in Figure 3.

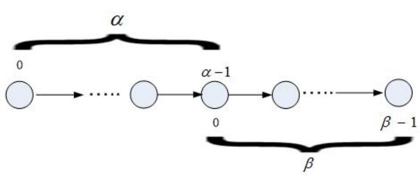


Fig. 3. A light-trail split into two light-trails of lengths $\alpha$ and $\beta$

The traffic on the first light-trail is given by Equation 11 and the traffic in the other by Equation 12. Clearly they can only set equal if $\alpha = \beta$, which requires an initial light-trail of odd length.

$$\frac{\alpha(\alpha-1)}{2} + (\alpha-1)(\beta-1) \tag{11}$$

$$\frac{\beta(\beta-1)}{2} + (\alpha-1)(\beta-1) \tag{12}$$

### G. Three-way Split

Trying to split a light-trail three ways as shown in Figure 4 is even more complex. The following derivation finds a formula for splitting a light-trail into three segments with almost equal traffic in the three segments. One formula is sufficient as we will show that the firt and third light-trails must be of equal length.

*Lemma 2.* A three way split with uniform traffic between all source-destination pairs served by the light-trail requires the first and the last segments to be of the equal size.

*Proof.* Consider a light-trail that has been split up into three segments of length $\alpha$, $\beta$, $\gamma$. Traffic on these light-trails are given by Equations 13, 14, 15 respectively.

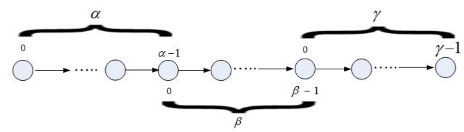


Fig. 4. A light-trail split into three light-trails of lengths $\alpha$, $\beta$, and $\gamma$

The bandwidth required in the segment of length $\alpha$ comes from the traffic generated and consumed internally($\frac{\alpha(\alpha-1)}{2}$) along with the traffic destined for segments of length $\beta$ which is $((\alpha-1)(\beta-1))$ and the traffic destined for segment of length $\gamma$ which is $((\alpha-1)(\gamma-1))$.

$$\frac{\alpha(\alpha-1)}{2} + (\alpha-1)(\beta-1) + (\alpha-1)(\gamma-1) \tag{13}$$

For middle segment of the light-trail, the bandwidth required also includes traffic generated by the nodes in segment of length $\alpha$ destined to nodes in the segment of length $\gamma$ and to the nodes in the segment of length $\beta$ which is $((\alpha-1)(\beta-1) + (\alpha-1)(\gamma-1))$.

$$\frac{\beta(\beta-1)}{2} + (\alpha-1)(\beta-1) + (\alpha-1)(\gamma-1) + (\beta-1)(\gamma-1) \tag{14}$$

The third segment as with the previous requires traffic which has a quadratic term in terms of its' own length from internal traffic, and traffic from each previous light-trail contributes traffic which is a product of this segments length and the previous light-trails' length.

$$\frac{\gamma(\gamma-1)}{2} + (\alpha-1)(\gamma-1) + (\beta-1)(\gamma-1) \tag{15}$$

Setting the first two equal we get.

$$\begin{aligned} \frac{\alpha(\alpha-1)}{2} + (\alpha-1)(\beta-1) + (\alpha-1)(\gamma-1) = \\ \frac{\beta(\beta-1)}{2} + (\alpha-1)(\beta-1) + \\ (\alpha-1)(\gamma-1) + (\beta-1)(\gamma-1) \end{aligned} \tag{16}$$

$$\text{or} \quad \frac{\alpha(\alpha-1)}{2} = \frac{\beta(\beta-1)}{2} + (\beta-1)(\gamma-1) \tag{17}$$

Setting the second and third equal we get.

$$\begin{aligned} \frac{\gamma(\gamma-1)}{2} + (\alpha-1)(\gamma-1) \\ +(\beta-1)(\gamma-1) = \\ \frac{\beta(\beta-1)}{2} + (\alpha-1)(\beta-1) + \\ (\alpha-1)(\gamma-1) + (\beta-1)(\gamma-1) \end{aligned} \tag{18}$$

$$\text{or} \quad \frac{\gamma(\gamma-1)}{2} = \frac{\beta(\beta-1)}{2} + (\alpha-1)(\beta-1) \tag{19}$$

Solving Equation 19 for $\frac{\beta(\beta-1)}{2}$ and substituting into Equation 17, and then by rearranging we obtain the following.

$$\frac{1}{2}\alpha(\alpha-1)-\frac{1}{2}\gamma(\gamma-1)=(\beta-1)((\gamma-1)-(\alpha-1)) \quad (20)$$

$$\text{or} \quad -\frac{\gamma^2-\alpha^2}{2}-\frac{\gamma-\alpha}{2}=(\gamma-\alpha)(\beta-1) \quad (21)$$

Assuming $\gamma \neq \alpha$ and then dividing by $(\gamma-\alpha)$ yields

$$\beta=\frac{1}{2}-\frac{1}{2}(\alpha+\gamma). \quad (22)$$

As length is an integer greater or equal to two for feasible solution, there is no solution to Equation 22. Thus $\gamma = \alpha$. This complete the proof.

Now, by substituting $\gamma = \alpha$ into Equation 17 or 19 and multiplying the equation by 2, we obtain the following.

$$\begin{aligned} \alpha(\alpha-1) &= \beta(\beta-1)+2(\alpha-1)(\beta-1) \\ \text{or} \quad \alpha(\alpha-1) &= (\beta-1)(\beta+2\alpha-2) \end{aligned} \quad (23)$$

Notice that $\alpha+\beta+\gamma-2=n$ or $\beta=n+2-2\alpha$. Substituting this in Equation 23 and simplifying yields

$$\alpha^2+(2n-1)\alpha+n(n+1)=0 \quad (24)$$

Solving for $\alpha$ and keeping only the positive sign for length, we obtain the following solution.

$$\alpha=\frac{-(2n-1)+\sqrt{8n^2+1}}{2} \quad (25)$$

Only for a very few values of $n$ such as $6, 35,$ and $204$, we obtain an integer solution for $\alpha$ (and therefore $\beta$). The corresponding light-trail splits are 3-2-3, 15-7-15, 85-36-85. The third light-trail is too big to realize physically and may need to split further. For other values of $n$, one will have to make an approximation. For example, for $n = 16$, we obtain $\alpha = 7.13$. In this case, we can use a split of 7-4-7. For large values of $n$, $\alpha+\gamma \approx \lceil 0.84n \rceil$ and $\beta = n+2-\alpha-\gamma$.

### *H. Recursive splitting*

At the expense of losing some flexibility, light-trail segmentation can be done recursively.

The formulas for splitting a light-trail the second or later times are slightly different from the initial splitting. The reason for this is that in most segments there is a certain amount of traffic $b$ that is generated before the light-trail segment that is being split. This traffic uses capacity on the light-trail segment that is being split, but this traffic will not use capacity uniformly between split sections since some of it is consumed by them internally.

Consider splitting a light-trail that is in the middle of a previously split light-trail. If this were the first light-trail segment we could repeat the analysis for splitting a two node light-trail and obtain $\frac{k}{2}(2m-k-1)=(n-k-1)\frac{m+k}{2}$ The correction to this formulism is just adding $b$ traffic to the first segment and $b-(k+1)$ traffic to the second segment. Thus it is best to split light-trail segment at $k=\frac{n-2}{3}$ where $n$ is the number of nodes in the trail being split and not the original light-trail.

## IV. Conclusion

In this paper we demonstrated that short light-trails with repeater nodes can provide more capacity for connections than long light-trails that are found as solution for traffic grooming. Realistically a light-trail should only be split a small number of times and we have provided methods and analysis on performing such splits. We have analyzed the cases for splitting a light-trail in two or three segments and derived exact relationship between the size of segments to equalize traffic handled by each of them. Our future work include studying traffic variations and the net impact on delay to bound the segment size from low end.

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